Appendix III. Gas-cooled Fast Reactor

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1.0 Gas-Cooled Fast Reactor (GFR)

The gas-cooled fast reactor (GFR) was chosen as one of the Generation IV nuclear reactor systems to be developed based on its excellent potential for sustainability through reduction of the volume and radiotoxicity of both its own fuel and other spent nuclear fuel, and for extending/utilizing uranium resources orders of magnitude beyond what the current open fuel cycle can realize. In addition, energy conversion at high thermal efficiency is possible with the current designs being considered, thus increasing the economic benefit of the GFR. However, research and development challenges include the ability to use passive decay heat removal systems during accident conditions, survivability of fuels and in-core materials under extreme temperatures and radiation, and economical and efficient fuel cycle processes. Nevertheless, the GFR was chosen as one of only six Generation IV systems to be pursued based on its ability to meet the Generation IV goals in sustainability, economics, safety and reliability, proliferation resistance and physical protection.

Goals and Criteria. Sustainability is the key goal for the GFR. This is based on the ability of this system to utilize a fast neutron spectrum, and thus the ability to conserve uranium resources. In addition, the closed fuel cycle will minimize waste through in an integral homogeneous recycling of all actinides (plutonium and minor actinides, e.g., Np, Am, and Cm) present in the spent fuel. One way to accomplish this goal would be to minimize the uranium feedstock with a self-sustaining cycle that only requires depleted or reprocessed uranium feed, thus utilizing a self-generating core with a breeding gain near zero.

Good economic performance will be accomplished through the use of a high thermal efficiency, compact power conversion unit utilizing direct or indirect cycles. In the case of high outlet temperatures (850°C), hydrogen production would also be possible. Unit power will be in the range of 300 MWe (modularity) to a larger 1500 MWe size. Generation IV objectives for construction time and costs will be also considered.

The current safety goals include the assumption of no off-site radioactivity release, which requires efficient, simple, robust, and reliable systems and physical barriers. At the core level, the use of refractory fuels with a very high capacity to confine fission products at high temperature (≥1600°C), and robust structural materials will be studied.

In keeping non-proliferation goals, the use of fertile blankets will be minimized or negated. This will avoid, as far as possible, separated materials in the fuel cycle. High burn-up, together with actinide recycling, will result in spent fuel characteristics (isotopic composition) that are unattractive for handling. In addition, minimizing spent fuel transportation will help non-proliferation concerns, and could be attainable if very compact facilities can be designed with on-site fuel treatment.

Finally, the range for the power density is a specific point to be mentioned. This value affects economics (minimization of fuel inventory, minor actinide production, fuel cycle cost, and compactness of the primary vessel), sustainability (fuel cycle with sufficient dynamics and minimizing the fuel needs for long term deployment), and safety (in particular decay heat removal in case of depressurization with loss of offsite power). Economics and sustainability call for higher values, and safety for lower values. The tentative range between 50 and 100 MW/m^3 appears to be a good compromise, which lies between HTGR values of about 7 MW/m^3 and classical LMFBR's at > 200 MW/m^3.

<u>*Design Options for the GFR.*</u> The current reference GFR system features a fast-spectrum, helium-cooled reactor and closed fuel cycle (see Figure 1). This was chosen as the reference design due to its close relationship with the VHTR, and thus its ability to utilize as much VHTR out-of-pile material and balance-of-plant technology as possible. Like thermal-spectrum helium-cooled reactors such as the Gas-Turbine Modular Helium Reactor (GT-MHR) and the Pebble Bed Modular Reactor (PBMR), the high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen or process heat with high conversion efficiency. The GFR reference design uses a direct-cycle helium turbine for electricity (42% efficiency at 850°C), and process heat for thermochemical production of hydrogen.

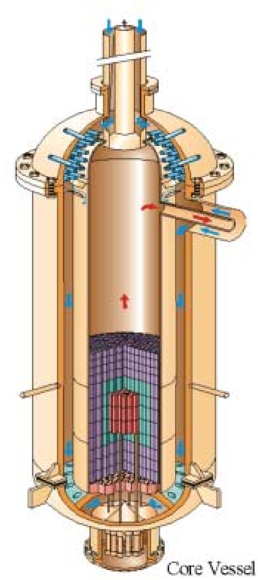

Figure 1. Possible GFR vessel and core configuration for a block/plate core.

The alternate design is also a helium-cooled system, but utilizes an indirect Brayton cycle for power conversion. The secondary system of the alternate design utilizes supercritical CO_2 (S-CO_2) at 550°C and 20 MPa (see Figure 2). This allows for more modest outlet temperatures in the primary circuit (~ 600-650°C), reducing the strict fuel, fuel matrix, and material requirements as compared to the direct cycle, while maintaining high thermal efficiency (~ 42%).

The optional design is a S-CO_2 cooled (550°C outlet and 20 MPa), direct Brayton cycle system. The main advantage of the optional design is the modest outlet temperature in the primary circuit, while maintaining high thermal efficiency (~ 45%). Again, the modest outlet temperature (comparable to sodium-cooled reactors) reduces the requirements on fuel, fuel matrix/cladding, and materials, and even allows for the use of more standard metal alloys within the core. This has the potential of significantly reducing the fuel matrix/cladding development costs as compared to the reference design, and reducing the overall capital costs due to the small size of the turbomachinery and other system components. The power conversion cycle is equivalent to that shown in Figure 2,

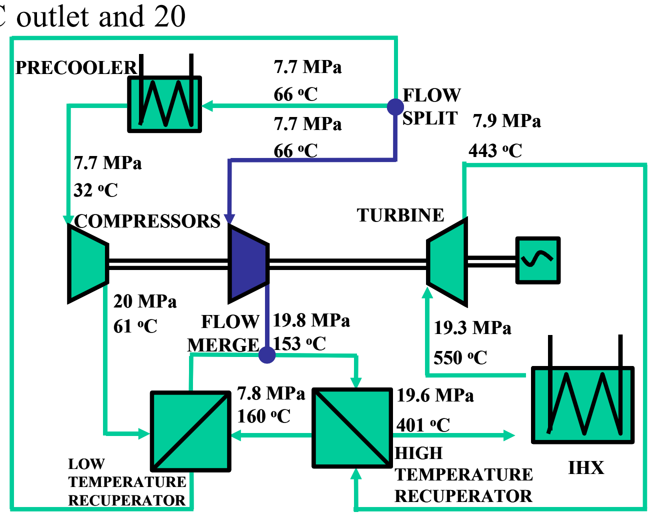

Figure 2. Schematic of the S-CO_2 recompression cycle.

where the IHX would be replaced by the reactor and reactor pressure vessel.

System Design and Safety. GFR R&D includes conceptual studies of a reference system, assessment of alternative options, analyses of the safety approach and of specific safety features, and the development of computational tools for these studies. Technological developments of fuel, components and sub-systems are conducted in the other R&D tasks. The system design and safety task aims at proposing and progressively updating the definition and performance assessment of the GFR while integrating the results of the technological R&D. In return, it contributes to orient and define the requirements for the technological R&D projects to meet the priority needs for assessing consistently the system viability and performance. The safety analysis of the reference concept will check the compliance with the Generation IV criteria. Early GFR research will have to offer the required flexibility to test still open options for the GFR.

The main goals of system design and safety include:

- Definition of a GFR reference conceptual design and operating parameters meeting the designs goals and criteria.
- Identification and assessment of alternative design features that fulfill Generation IV goals and criteria.
- Safety analysis for the reference GFR system and its alternatives.
- Assessment of economic performance.
- Development and validation of computational tools needed for the design and the analysis of operating transients (design basis accidents and beyond) – Benchmarking and validation against experimental data – Specification of required test facilities to obtain missing experimental data for the qualification of calculation tools.

Key dates are:

- 2004-2005. Exploratory studies.
- 2006-2013. Pre and conceptual design, safety options report.
- 2014-2018. Preliminary design, preliminary safety report.
- 2019-2025. Final design and construction.

Fuels. System design will be affected by the choice of primary coolant, whether a direct or indirect power conversion cycle is used, and the core geometry (i.e., block, plate, pebble, etc.). In addition, the fuel and fuel matrix/cladding to be used becomes a key issue in the development of the GFR. The trade-off between high conductivity and high temperature capabilities has led to the choice of ceramics, including refractory ceramics. The reference fuel matrix for the Generation IV GFR is a cercer dispersion fuel, based on a balance between conductivity and high temperature capability. Figure 3 is a graphical representation of the fuel types being considered.

The reference fuel designs are based on dispersion fuels (either as fibers or particles) in an inert plate/block type matrix, with options to use particle fuel in an inert pebble matrix, or solid solution fuel clad in a refractory ceramic (e.g., SiC/SiC composites). The reference fuels chosen for the GFR are UN and UC for their high heavy metal density, high conductivity, and minimal impact on neutron spectrum (although limited irradiation data exists). The matrix/cladding materials are dependent on the coolant and operating temperatures, and can be classified into three categories: ceramic (for high temperatures), refractory metal (for modest to high temperatures), and metal (for modest temperatures). As the fuels are of ceramic composition, the resulting fuel forms can be classified into two categories: cercer and cermet. The fuel fibers, or "sticks" (see Figure 3), would be extruded into the matrix, where the matrix would have a "honeycomb" appearance. The particle fuel may be coated, but, unlike the thermal spectrum gas

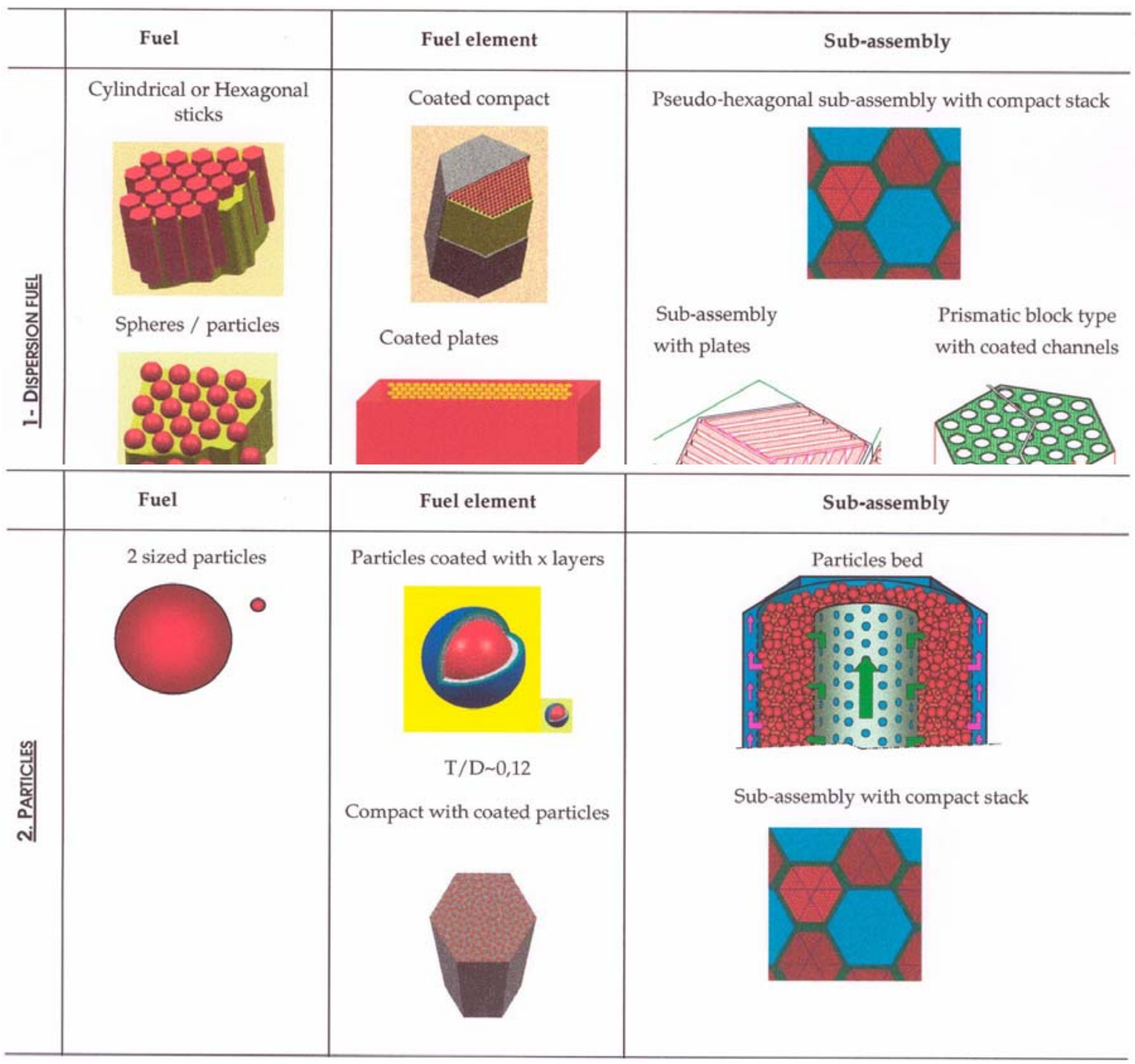

Figure 3. GFR fuel types.

reactor fuel, will most likely have one coating to maximize the heavy metal content within the matrix.

Key dates are:

- 2004–2014. Continuous acquisition and refining of basic data on inert materials and actinide compounds, definition of reference and backup fuel concepts, and selection of manufacturing processes.
- 2005–2018. Irradiations (screening and optimization) in existing reactors.
- 2012–2019. Fabrication and irradiation of prototype candidates fuel assemblies under typical GFR conditions in the ETDR and performing of the necessary in-pile safety tests in the adequate experimental reactors.

In-Core Materials. These materials will have to withstand fast-neutron induced damage and high temperatures; up to ~1600°C during abnormal situations. Ceramic materials are the reference, and composite cermet structures or inter-metallic compounds will be considered as a backup.

The recommended R&D is closely linked to the fuel development program with a screening phase, then material irradiation and characterization, ending with the selection of a reference set of materials for core structural materials in 2006. Optimization and qualification under irradiation will occur from 2006 to 2016. The objective is to be in a position to fabricate and irradiate prototype sub-assemblies in 2012 – 2019.

The program goal is to select the materials that offer the best compromise regarding:

- Fabricability and welding capability.
- Physical, neutronic, thermal, tensile, creep, fatigue, and toughness properties and their degradation under the prototypical GFR neutron flux and dose.
- Microstructure and phase stability under irradiation.
- Irradiation creep, in-pile creep, and swelling properties.
- Initial and in-pile compatibility with Helium and/or CO_2, including impurities.

The main core applications are the following inert structures involved in the different fuel concepts, and are closely tied to the fuel task:

- Basket containing the particle/pebble fuel.
- Casing & gas tubing for the composite fuel.
- Clad for pin-based fuel.
- All other assembly structures.

Efforts will be focused on the most promising carbide ceramics (preferred option): SiC, ZrC, TiC, NbC; or other materials like nitrides (TiN, ZrN), oxides (MgO, $Zr(Y)O_2$) and possibly Zr, V or Cr based metallics as part of the CER/MET composite inert material, or intermetallic compounds like Zr_3Si_2.

Viability and Performance Phase Research. The objectives and endpoints of the viability and performance phases, as defined in the Roadmap, can be seen in Table 1 below. The tasks that were detailed previously, i.e., system design and safety, fuels, and in-core materials, play a crucial role in determining the viability of the GFR as a system. Not included in the discussion above is development of the fuel cycle, which would naturally follow the development and viability of the reference fuels. Although not explicitely mentioned above, this particular task falls under the NTD for separations within the Advanced Fuel Cycle initiative (AFC). As the reference fuel(s) become more defined, including the matrix/cladding, requirements for the fuel cycle itself will become more clear.

Table 1. Viability and performance phase objectives and endpoints.

Viability Phase Objective:	Performance Phase Objective:
Basic concepts, technologies and processes are proven under relevant conditions, with all potential technical show-stoppers identified and resolved.	Engineering-scale processes, phenomena, and materials capabilities are verified and optimised under prototypical conditions

Viability Phase Endpoints:	Performance Phase Endpoints:
Preconceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams.	Conceptual design of the entire system, sufficient for procurement specifications for construction of a prototype or demonstration plant, and with validated acceptability of disposal of all waste streams
Basic fuel cycle and energy conversion (if applicable) process flowsheets established through testing at appropriate scale.	Processes validated at scale sufficient for demonstration plant
Cost analysis based on preconceptual design	Detailed cost evaluation for the system
Simplified PRA for the system	PRA for the system
Definition of analytical tools	Validation of analytical tools
Preconceptual design and analysis of safety features	Demonstration of safety features through testing, analysis, or relevant experience
Simplified preliminary environmental impact statement for the system	Environmental impact statement for the system
Preliminary safeguards and physical protection strategy	Safeguards and physical protection strategy for system, including cost estimate for extrinsic features
Consultation(s) with regulatory agency on safety approach and framework issues	Pre-application meeting(s) with regulatory agency

Overall Schedule and Budget. Based on all viability and performance phase work, a proposed GFR schedule and budget through 2020 is shown in Figure 4, below.

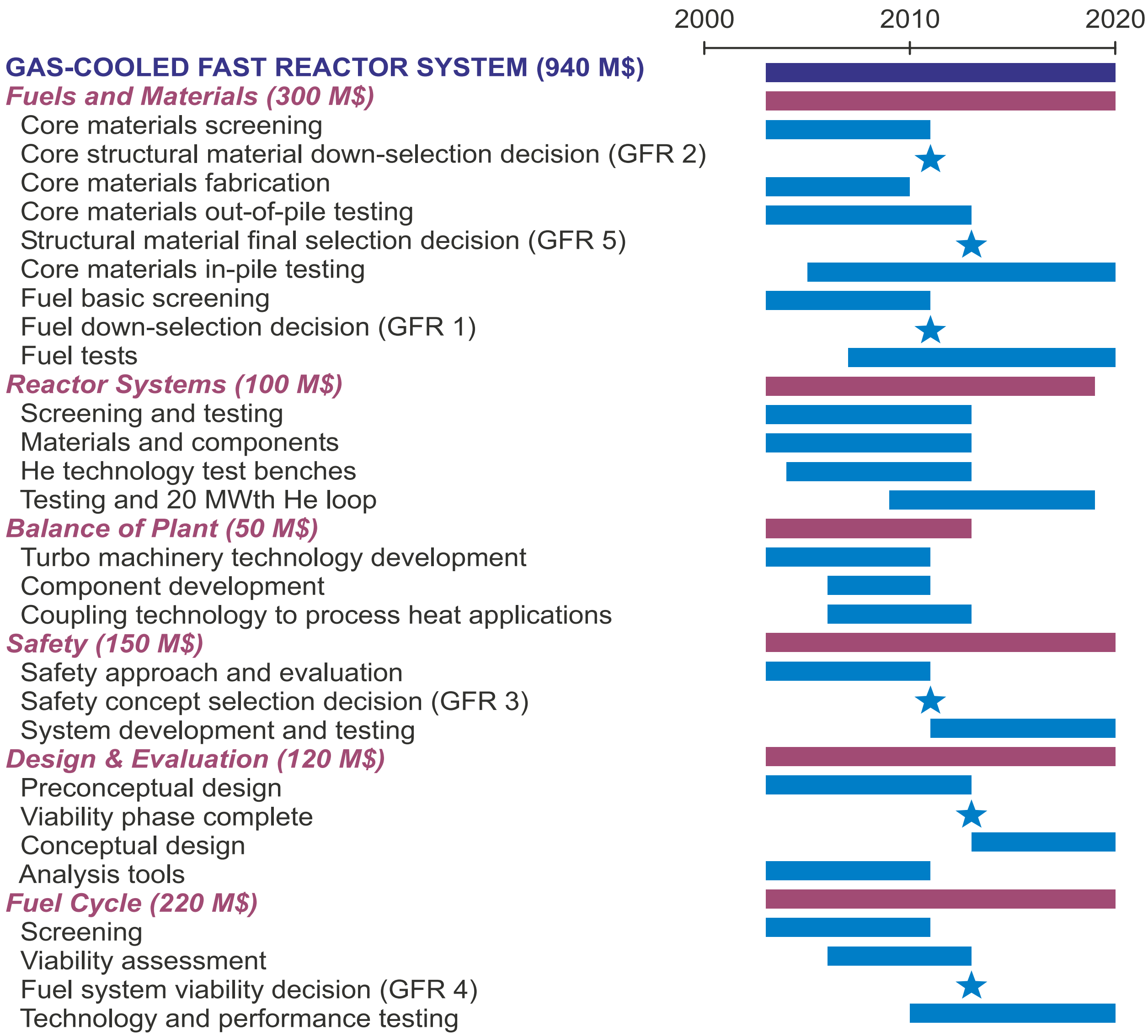

Figure 4. Total R&D budget for the GFR.

The development of the GFR, and thus the estimated R&D budget, is intended to be shared by a group of international partners that are members of the Generation IV International Forum (GIF). The GFR currently has eight GIF members that have expressed interest in its development: the European Union, France, Japan, Korea, South Africa, Switzerland, the United Kingdom, and the United States. Assuming that all the GIF members share equally in the R&D cost for the development of the GFR, each member would need to contribute $117.5M before 2020. However, one of the eight GIF members that expressed interest in the GFR has elected to participate at a minimal level, leaving seven members that are (or will be) performing research. This leaves each member with a total of $134.3M of research through 2020, or approximately $8M per year if levelized evenly through 2020.

However, the current plan deals only with the viability phase of the work. Thus the Level 2 and higher activities needed for successfully demonstrating the viability of the GFR are discussed in greater detail in the following subsections.

1.1 System Design and Evaluation

The major activities within the System Design and Evaluation activity include system design and evaluation of passive and active safety systems for decay heat removal; system control and transient analysis; design and construction of experiments for thermal-hydraulic/safety tests, and coolant chemistry control; and code development/adaptation for neutronic and thermal-hydraulic analysis. These activities are detailed below.

1.1.1 Safety Concept Selection

This activity includes the down selection and optimization of safety systems for decay heat removal (short, intermediate, and long term), including physics and thermal-hydraulic analyses for the reference and optional systems. Current studies show that a passive decay heat removal system is possible through heavy gas injection (i.e., using accumulators containing nitrogen or carbon dioxide), but may be further enhanced by coupling to an active system. Optimization studies will include containment building design and viability, as natural convective (passive) cooling may require a pressurized containment.

1.1.2 Reactivity Control and Transient Analysis

As this reactor two of the three options will use a direct-cycle for power conversion, reactor control issues will need to be identified and analyzed; this includes accident scenarios such as ATWS events, and the reactor's ability to shutdown passively through negative reactivity coefficients (e.g., expansion, etc.). Initiators for other transient events will also be identified through limited scope PRA.

1.1.3 Integrated Test Facilities and Component Development

Heated loop, volume, and other experiments will be designed and constructed that can operate with high temperature helium (850°C) or high pressure CO_2 (20 MPa, 550°C), and will be used to: measure the pressure drop, measure the heat transfer coefficient, perform passive safety experiments (e.g., containment response), and develop coolant monitoring techniques and chemistry control at prototypical GFR operating conditions. Simulation of various core geometries will be possible including block, pin, plate, and/or pebble cores.

1.1.4 Code Development

Adaptation of existing calculation tools to support concept development and safety evaluations of the GFR will be performed. Neutronics and thermal-hydraulics/safety tools will be the focus. Future activities will focus on verification and validation. This activity will be coordinated through the Design and Evaluation Methods NTD.

1.2 Materials

The activities within the Materials activity include screening and testing of high temperature materials; corrosion studies using supercritical CO_2, etc. These activities are detailed below.

1.2.1 High Temperature Materials

Screening and testing of candidate high temperature materials will be performed, including fabricability and survivability testing. Leading in-core and out-of-core candidates will then be tested appropriately (e.g., in-core materials will be tested in-pile for irradiation damage).

1.2.2 Supercritical CO_2 Corrosion

Screening of potential/candidate materials for in-core and ex-core service will be performed, where high pressure and medium temperatures will be used during the tests. In addition, radiolysis experiments will be performed to identify the chemical species that are formed in the CO_2 coolant during irradiation.

1.3 Energy Conversion

The activities within the Energy Conversion activity include feasibility studies of a direct Brayton cycle; and development of the turbomachinery for helium and CO_2 systems. Many of these activities have been identified as crosscutting, and will be planned/coordinated/executed with the Energy Conversion NTD. They are detailed below.

1.3.1 Balance-of-Plant

Feasibility issues regarding demonstration of the Brayton cycle for both helium and supercritical CO_2 will be studied; including single shaft or multi-shaft systems. Some of these issues can be resolved with an integral test facility, and/or small-scale component demonstrations.

1.3.2 Turbomachinery Development

Turbine, compressor, and other component design will be initiated; with special attention being paid to the turbine and compressor designs. Viability will be assessed, as well as some optimization. This activity will be closely coupled to the balance-of-plant activity.

1.4 Fuels and Fuel Cycle

The activities within the Fuels and Fuel Cycle activity include fuels feasibility, fabrication, and testing; recycle process feasibility studies; and studies on the viability of refabrication. These activities are detailed below, and will be closely coordinated with the AFC work.

1.4.1 Fuels Feasibility

Fuel survivability for high temperature/high fluence environments, and coolant/fuel incompatibilities for medium temperature fuels, will be assessed (including carbide, nitride, oxide, and metallic fuels). Comparisons of benefits/challenges of each fuel type will be performed. Special attention will be paid to those fuels that may be able to support large fractions of minor actinides. Modeling of fuel behavior will be used to the extent possible as a tool to evaluate feasibility, however a final determination can only be made through a program of irradiation testing.

1.4.2 Fabrication and Testing

While fabrication of conventional ceramic and metallic fuels is fairly well understood, both carbide and nitride fuel forms will need to be developed. Economic fabrication techniques will be sought, as well as appropriate matrix materials for dispersion fuels. Irradiation testing of fuels (including those containing minor actinides) will also be performed.

1.4.3 Process Feasibility

Recyclability of candidate fuels and matrix materials will be assessed, which will include possible use of current technologies (e.g., pyro, aqueous, and/or other dry processes). For those fuel forms that are beyond current technologies, new processes will be evaluated for both technical and economical viability.

1.4.4 Refabrication and Testing

Equilibrium and heavy minor actinide bearing fuels will tested for refabricability (i.e., remote fabrication techniques will be selected and tested). The closed fuel cycle will be tested through irradiation and processing of the candidate fuels.

1.5 Budget, Milestones, and Tasks

1.5.1 Required Budget

Table 2 gives an estimated breakdown of the activities for the required budget to address the viability issues.

Table 2. Summary of GFR required budget and level 2 activities ($K).

Technology	**FY 04**	**FY05**	**FY06**	**FY07**	**FY 08**	**FY 09**	**FY 10**	**TOTAL**
System Design & Evaluation								
Materials								
Energy Conversion								
Fuels & Fuel Cycle								
Total								

The budget reflects the U.S. contribution to the development of the GFR. Other GIF members participating will also contribute to the R&D as discussed earlier.

1.5.2 Milestones

The major milestones below reflect those of the Roadmap, and the current GFR international R&D plan, as formulated by the GFR Steering Committee:

- Safety concept selection – 2012
- Core structural material down-selection – 2012
- Fuel down-selection – 2012

It is important to note that a major U.S. milestone is a fast spectrum system down selection by 2010, and thus the viability phase work must be completed by that date. The corresponding work/milestones for the down selection are:

- FY 2006 - Initiating a GFR fuel irradiation program.
- FY 2007 - Complete basic GFR core design and systems safety analysis sufficient to support design safety goals.
- FY 2008 – Complete first phase of advanced GFR fuel irradiation, and select the safety system(s) to finalized pre-conceptual design.
- FY 2010 – Finalize pre-conceptual design in sufficient detail to permit a comparison with the other two fast reactor technologies, on economics, proliferation resistance, safety and licensing, and sustainability.

1.5.3 Tasks

The tasks needed to support the major milestones include:

- Safety concept selection
  - Pre-conceptual system design, and accident analysis
    - Physics and thermal-hydraulic analyses
    - Code selection/development, verification, and validation
  - Design and/or identification of integrated test facilities for thermal-hydraulic testing, and development of test plan
  - Construction of integrated test facilities for thermal-hydraulic testing, and/or initiation of safety tests
- Core structural material down-selection
  - Screening
  - Fabrication
  - Out-of-pile testing
  - In-pile testing
- Fuel down-selection
  - Screening
  - Fabrication
  - Out-of-pile testing
  - In-pile testing